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Measurement of Velocity and Temperature Profiles in Low-Speed, Turbulent Non-Isothermal Flows

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Notice

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NOMENCLATURE

d	distance between thermocouples in a pair
H	height of ceiling above burner
m	number of data points corresponding to a given time shift
n	data point index
N	total number of data points in a record
r	radial distance from stagnation point of plume on ceiling
R	cross correlation function
V	ceiling jet velocity
V_x	thermocouple voltage output
x_1	forward thermocouple in a pair
x_2	aftward thermocouple in a pair
ρ	cross correlation coefficient
τ	time shift between thermocouple records

MEASUREMENT OF VELOCITY AND TEMPERATURE PROFILES IN LOW-SPEED, TURBULENT, NON-ISOTHERMAL FLOWS

Vahid Motevalli, Colin H. Marks and Bernard J. McCaffrey*

ABSTRACT

A probe has been developed utilizing thermocouples as sensors which, together with associated data-reduction and processing equipment, makes it possible to measure velocity and temperature profiles in low-speed, turbulent, non-isothermal flows. The technique presented here might be well suited for transient processes where simultaneous measurements are required in multiple locations. This probe was devised in order to measure the velocity and temperature profiles in the jet formed under a ceiling when a buoyant plume from a fire impinges on the ceiling.

The probe and the technique used in this work is based on the earlier concept proposed by G. Cox in which the temperature-time records from a pair of thermocouples, one downstream of the other, are cross-correlated to determine the flow velocity.

Preliminary data has been collected for the velocity and temperature profiles in ceiling jets for small fires. The velocity measurements have undergone extensive calibration tests to determine the degree of confidence in these measurements, calibration results are also included here. This work shows that the technique presented is quite reliable and can predict the mean velocity of turbulent, low-speed, non-isothermal flows within 5% confidence while producing simultaneous mean temperature measurements.

1. INTRODUCTION

This paper describes a probe which can be used to simultaneously obtain mean velocity and mean temperature measurements in low-speed, turbulent, non-isothermal flows. The objective which motivated this work was the study of the transient characteristics of a plume-driven ceiling jet. The ceiling jet forms when a buoyant plume from a fire impinges on the ceiling. This jet, for small fires, has a low speed, it is turbulent with large eddy structures and has large temperature gradients. Another important consideration in the study of the characteristics of the ceiling jet is the need to obtain the velocity and temperature measurements at several locations within the jet simultaneously under transient as well as steady conditions. As explained by Cox [1], conventional instrumentations may not be able to accurately measure the velocity of low-speed, non-isothermal, turbulent flows having large scale eddies.

A technique first used by G. Cox [1,2,3] provides the desired capability to measure mean velocity and mean temperature profiles, using the same probe,

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simultaneously in non-isothermal flows. This work and previous efforts by the authors [4] demonstrate the capability to measure mean flow temperatures and velocities simultaneously while examining the reliability of the results employing a modern, computer-controlled data acquisition and data reduction system. The technique discussed here uses the temperature of the fluid particles as a tracer and obtains the mean velocity of the fluid particles as a result of the measured travel time from one sensor to another, the second being located a short distance downstream of the first. A pair of thermocouples, used as temperature sensors, separated by a distance, d, in the flow direction produces two temperature-time records. The mean temperature of the fluid over the sampling period can be directly obtained from the thermocouples. The mean velocity measurement, however, requires more data manipulations.

If the turbulent eddies within the fluid move without distortion then the second thermocouple would observe a shifted record, in time, of that monitored by the upstream thermocouple, Fig. 1. This time shift, τ, is the time needed for the turbulent eddies to travel the distance d between the thermocouple pairs. The mean stream-wise velocity of the fluid can thus be determined by dividing the distance d by time τ. Cox has shown that it is possible to determine the time shift by cross correlating the temperature-time records of a pair of temperature sensors. The average time shift between a record pair is determined as the time shift which results in the maximum correlation between the two records. The correlation function, $R_{x_1x_2}$, is defined as follows:

$$R_{x_1x_2} = \lim_{T\to\infty} \frac{1}{T} \int_0^T V_{x_1}(t) V_{x_2}(t+\tau)\, dt \qquad (1)$$

where V_{x_1} and V_{x_2} are the data records and T is the sampling time. Since the data is collected over a finite time, the correlation function is normalized to eliminate the effect of amplitude variations in the temperature records. These variations are due to the diffusion of energy taking place while eddies travel between the sensor pairs. The normalized correlation function is called the correlation coefficient ρ_{x_1,x_2}, and can be written in the following form as a numerical expression [5,6].

$$\rho_{x_1,x_2} = \frac{R_{x_1,x_2}}{\left[\frac{1}{N-m}\sum_{n=1}^{N-m} V_{x_1}^2(n)\right]^{1/2} \left[\frac{1}{N-m}\sum_{n=m}^{N} V_{x_2}^2(n)\right]^{1/2}} \qquad (2)$$

where

$$R_{x_1,x_2}(m) = \frac{1}{N-m}\sum_{n=1}^{N-m} V_{x_1}(n)\, V_{x_2}(n+m) \qquad (3)$$

and N is the total number of data points. The integer number, m, corresponds to the time-shift translated into number of data points by which one record is shifted with respect to the other one. The correlation coefficient, ρ_{x_1,x_2}, has a value of zero when there is no correlation between the two records, and a value of 1.0 when they correlate perfectly. The maximum value of the coefficient corresponds to a data record shift m which can be translated to a time shift for a known sampling rate. The procedure, outlined in this paper, describes how the average time-shift over the record length and consequently the mean flow velocity averaged over the distance between the sensors is obtained.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The experiment setup is shown in Fig. 2. It consists of a methane-air burner whose outlet is level with an artificial floor, an insulated ceiling, the probe and the data acquisition and processing system.

2.1 Probe

The probe consists of 8 pairs of 0.001" dia. type E (chromel - constantan) thermocouples stretched between vertical supports as shown in Fig. 3. Using this configuration, nearly simultaneous measurements can be made at 8 different locations within the ceiling jet. Type E thermocouples have a high sensitivity and the selected size provides a small response time. The calculated time constant of the thermocouples based on a steady-flow convection coefficient at 0.5 m/s is approximately .05 sec. This constant, however, is strongly affected by the convection coefficient. The vertical supports are made of two rectangular pieces of silicon glass, fixed at the base and separated by 10.16 cm (4 inches). The thermocouple beads are positioned at half point between the holder arms and aligned one behind the other to an accuracy of 0.4 mm (1/64 inch). The ceiling jet passes between these arms, which are far enough apart that they do not disturb the flow about the beads. The probe is held in place by a stand which provides 3-dimensional positioning of the probe under the ceiling. The fine thermocouple wires were connected to insulated, shielded E-type extension wires. These wires were brought to an insulated reference junction whose temperature was continuously monitored.

2.2 Data Acquisition System

The data acquisition system consists of a 16 channel signal conditioning system (16 channel amplifier), a multiprogrammer data acquisition system, and a computer to control the multiprogrammer and to perform the data processing.

Voltage signals from the thermocouples are amplified by a factor of 850 before passing into the multiprogrammer. The gain of each amplifier module

was accurately set to within 0.005% and the amplifier output zero offset was adjusted to within 1 mV for a shorted input.

The multiprogrammer has a 16 single-ended channel FET scanner card with its associated scan control pacer card. A 500 kHz analog to digital converter in the multiprogrammer allows up to a 500 kHz sampling rate, but this speed is limited by the scanning rate of 100 kHz of the FET scanner card. In order to collect data at high speeds, a 64k word (each data point is a word and is 2 bytes long) memory card is used in the multiprogrammer to store the data as fast as they are collected for later transfer to the computer.

2.3 Data Collection and Processing

Data from each experiment are stored in binary data files. For each record, there exists a number of data points which equals the product of the sampling frequency and the sampling period. Temperature data are rather simply obtained via averaging the temperature measured by the thermocouple pair. The ceiling jet temperature is calculated from the thermocouple voltages using the thermocouple voltage to temperature conversion equations. To calculate the velocity, however, more complicated software has been devised which utilizes Eq. (2) for the data processing. The Golden Section method [7] is used to find the maximum value of ρ_{x_1,x_2} within the time interval of interest with the least number of coefficients actually calculated. The use of the Golden Section method reduces the data processing time of computing correlation coefficient by a factor of 10 compared to the time required to compute the correlation coefficient for every time shift increment.

2.4 Considerations in Data Collection

The uncertainty in the velocity is due almost entirely to the uncertainty in τ, since the distance, d, can be measured with excellent accuracy. Also involved, although indirectly, is the magnitude of the maximum value of ρ_{x_1,x_2}, since, as it decreases, the confidence that the correlation is meaningful decreases. The correlation coefficient decreases as d is increased because the turbulent eddies are not frozen as they move along, but instead change their shape and size. This causes the temperature-time records from the thermocouples in a pair to become increasingly dissimilar.

Because τ is obtained numerically, it cannot be determined with any greater precision than the sampling period between successive readings from a given thermocouple. This period clearly decreases as the sampling frequency increases. The percent error in determining τ and consequently the actual flow velocity is decreased as τ increases. For a given velocity, τ becomes greater as d increases; thus, a greater d reduces the percent error in velocity measurements.

To provide some sense of the magnitude of τ, and the order of magnitude of the sampling rate needed, consider a "typical" case with d = 2 cm and V = 0.5 m/sec. τ is then 2 cm÷(50 cm/sec), or 0.04 sec. For instance, in order to

make the error in τ less than 5%, the sampling period per thermocouple would have to be no more than 5% of 0.04 seconds, or 2 milliseconds. This corresponds to a sampling frequency per thermocouple of 500 Hz. Since sixteen thermocouple signals are being sampled, the sampling frequency selected for the data acquisition must be sixteen times this value, or 8 kHz. For the same maximum percent error in τ, the sampling rate could be decreased by a factor of two if d were doubled. Generally, a correlation coefficient of larger than 0.5 is desired to ensure good correlation and d is controlled by the degree of correlation, i.e., d can be increased to any distance only if the correlation coefficient does not fall below a desired value and spatial resolution does not suffer.

The percent error in τ and hence in V can be decreased by sampling at a high rate. Sampling at a high rate, however, is limited by the storage capacity of the computer, and by the increased data reduction time.

The data record length is another factor that must be considered. If it is not long enough to include a sufficient number of fluctuations, the true mean velocity cannot be obtained. In this case, for example, repeated measurements of the velocity of a stream whose mean velocity is constant would not yield the same velocity each time. If the record length is too long, the transient characteristics of the mean flow may be lost and, in addition, the storage capacity of the computer may be exceeded.

Because of the large number of factors to be considered, the selection of the sampling rate, record length and distance between thermocouples in a pair was carried out by trial and error after some investigations [8]. As a result of these investigations a sampling rate of 154 Hz/channel (overall sampling rate of 2464 Hz) and a record length of 10 seconds were selected for data collection.

In order to generate complete velocity and temperature profiles for a given radial location and a given fire strength, the probe had to be placed at two or more vertical distances from the ceiling. The relocation of the probe is done under the assumption that the experiment is closely reproducible when rerun to obtain the data at the lower probe setting.

At present, the distance, d, between the forward and rear thermocouples is fixed at 50 mm. This distance was selected through a series of experiments at ceiling steady state conditions. The cross correlation coefficient was used along with observations of plots of the data to determine how well the thermal fluctuations were preserved while traveling between the fore and back thermocouples as the distance separating the thermocouples was altered. In addition, the actual radial location of velocity and temperature measurements and uncertainty in velocity measurements were two major consideration in selecting this distance. The radial location for the mean velocity and temperature measurements is assumed to be at a point half way between the rear and forward thermocouples. The distance d must be selected such that it is much smaller than the characteristic depth of the ceiling jet, so that the eddies do not distort appreciably during the time that they move from the front thermocouple to the rear one. Comparison of d with the ceiling jet thickness estimated from Cooper's equations [9] and from Alperts' measurements [10] show that this requirement was satified for the measurements reported herein.

3.0 RESULTS

3.1 Calibration

One factor that can cause error in the velocity measurements is the difference in the bead size as reflected in the time constant of the thermocouples in each pair. Other errors due to sampling rate and signal quality have been already discussed. If both thermocouples do not have the same time constant, their time lags relative to the true temperature time history of the flow will differ. Thus the fluid velocity determined from the cross correlation of the temperature records would be smaller or larger than the correct value. The exact sizes of the thermocouple beads are unknown and the magnitude of the convection coefficients are not accurately known in flows such as those in question. To estimate the bead-size difference effect, a velocity profile in a ceiling jet under steady state conditions was obtained with the thermocouples in one orientation, and then with the thermocouples in a reversed orientation. The test was carried out using a small fire, approximately 1.0 kW, under a fiberboard ceiling at an r/H value of about 0.5. Each data point represents a mean velocity value averaged over 3 minutes using twelve 10 seconds long data records collected every 5 seconds. The test results are shown in Fig. 4. It is clear that the differences in the measured velocity due to the thermocouple orientation are small, less than 5%, except for one pair with the largest velocity difference of 9% with respect to the average value of the two orientations. Although Fig. 4 shows that the error due to thermocouple pair orientation is small, it does not conclusively pinpoint the absolute accuracy of the measurements since the actual absolute velocity of the jet is not known.

The most important concern in the use of the technique described here is the degree of confidence in the velocity measurements. Since, as mentioned earlier, other known measurement techniques have been determined to be generally ineffective or unreliable for low-speed, turbulent, non-isothermal flows, a scheme had to be devised to compare the velocity measurements made using the thermocouples with those obtained with an independent velocity measuring device. Techniques, such as Laser Doppler Velocimetrey, LDV, and hot-wire measurements are both much more complicated and expensive for multipoint measurements. LDV measurements and simultaneous temperature measurements by optical techniques have not been widely used in such flows. Hot-wire measurements in highly non-isothermal flow with large eddies and temperature fluctuations are not very easy to make and are not very reliable. Because of the above reasons a pitot-static tube was used for the calibration.

The calibration device was constructed from a short horizontal PVC pipe, 40.77 mm I.D. Air supplied at the inlet of the pipe was monitored by a National Bureau of Standards calibrated flowmeter. Several fine mesh screens in the pipe were used to straighten the flow. At two pipe diameters upstream of the outlet of the pipe a helical shaped heating coil with a diameter of 4.8 mm (3/16"), made of nichrome wire, was placed with its central axis aligned approximately with the centerline of the pipe. More screens were placed downstream of the heating coil, at the pipe exit, to eliminate any velocity

deficit caused by the coil. The heated wire induced thermal fluctuations in the flow. These fluctuations were needed to trace the flow by the thermocouple sensors.

The velocity at the pipe exit was checked by a 3.175 mm diameter pitot-static tube connected to a capacitance differential pressure sensor with a range as low as 10^{-4} mm Hg. The probe was placed at the pipe exit with d set at 30 mm. Two different flow rates rates, 62.7 liters/min, flow #1, and 47.9 liters/min, flow #2, were selected for the calibration.

The pitot tube and thermocouple measurements were performed simultaneously for both flow rates. The pitot tube was positioned behind the top thermocouple pair and the pipe was traversed vertically to obtain the velocity profile. The sampling rate was set at 3240 Hz thus providing a resolution of 1% on selecting the correct τ. The results for this calibration, presented in figure 5, show excellent agreement between the pitot tube and thermocouple measurements. The measurements for the lower flow rate case displayed a higher difference between thermocouple and pitot tube measurements. The larger errors at the lower flow rate may be due to buoyancy effects or limitations of the pitot-tube pressure transducer.

An important factor in obtaining good correlation and thus reliable velocity measurements is the strength of the thermal fluctuations. At very low pipe velocities, the amplitude of thermal fluctuations is reduced since the vortices shed from the heating coil are smaller and have reduced temperature gradients. In Fig. 5, the data points close to the top edge of the calibration pipe especially demonstrate the effect of buoyancy on distorting the velocity measurements, and low correlation values were computed for these points due to smaller thermal fluctuations. Near the pipe centerline, however, the correlation coefficient was quite high.

To check every thermocouple pair in the probe, a test was carried out with the pitot tube positioned behind each one. The thermocouple pairs were aligned with the centerline of the pipe one at a time. Table 1 shows the results of this run. The pitot tube measurements and thermocouple values are in agreement to less than 5% of the average of the two measurements for all pairs.

Although it would have been preferable to run the calibration at velocity ranges closer to the ceiling jet velocities, i.e. about 0.5 m/s, the strength of the thermal fluctuations was a limiting factor as described above as well as the reliability of the pitot-static velocity measurements at low velocities. This very factor, however, strengthens the merits of this calibration since the actual ceiling jet contains much stronger thermal fluctuations, thus enhancing the capability of this technique to predict the velocity of non-isothermal, turbulent flows with large thermal fluctuations. Furthermore, the scale of turbulence in the pipe flow is smaller thus causing the eddy deformation time scale in the pipe to be smaller than that in the ceiling jet, and the generally lower velocity of the ceiling jet allows a more accurate determination of τ.

3.2 Velocity and Temperature Profiles

Some preliminary results from the ceiling jet measurements for a 0.5 KW and 2.0 KW fire are presented here. The velocity and temperature profiles for 4, 10, 15, 20, 25 and 29 minutes after the start of the 0.5 KW fire are plotted in Fig. 6. The data record length was 10 seconds and a total of 5 records were used for each averaged value. All of the data were sampled at 154 Hz/channel (overall sampling rate of 2464 Hz) for d=5 cm thus producing a resolution of about 5% in τ. The temperature difference represents the difference between the absolute temperature of the ceiling jet and the ambient temperature. The data yields well-formed profiles and the scatter seems to be mostly due to combining the data from two runs for two different probe positions.

To demonstrate the transient measurement capability of this technique, Figures 7 and 8 are selected to show the velocity and temperature profiles at 5 seconds into the run for 0.5 KW and 2.0 KW fires. Each of these profiles are formed from a 10 second long data record, and again it should be noted that the probe had to be lowered to a new position to obtain all the data points. Some of the scatter, is of course, due to a possible timing difference between the start of data collections in the two runs. The Figures 6-8 show a slow fall-off of the velocity which appears to be consistant in most of the measurements. The free boundary of the ceiling jet is hardly approached, based on [9,10]. The correlation coefficient and the observed correlation between the temperature-time records pair are typically very good. Figures 9(a) and (b) show typical temperature-time records obtained from a 0.5 KW fire (at r/H=0.5) at 2 mm and 60 mm distance from the ceiling respectively. These figures demonstrate that the slow fall-off of the velocity is not due to a significant drop in correlation between data record pairs. This is particularly significant since a 0.5 KW fire is quite weak and the worst cases of correlation would be expected for this fire strength. The profiles at t=5 seconds actually show the mean flow velocity and temperature profiles over the first 10 seconds from the start of the fire and despite the 5% tolerance on the values plotted and combining the data from two different runs (for two different probe positions), the scatter in the data seems to be quite acceptable.

4.0 CONCLUSIONS

The technique presented here is deemed to be quite suitable for low-speed, turbulent, non-isothermal flow measurements. Among its important advantages are the information gathered, i.e., temperature and velocity profiles simultaneously, and that the sensors are as minimally disturbing as hot wires. In addition, the probe and technique presented is comparatively easy to apply for multi-point measurements.

Although pitot tubes are used to examine the precision of the thermocouple probe in velocity measurement, it is the pitot tube measurements that are not very reliable at low velocities of 0 to .5 m/s. In addition, pitot tubes dis-

turb the flow at the point of measurement much more than the probe used in this work, thus further highlighting the suitability of the thermocouple probe and this technique.

The calibration clearly demonstrates that a 5% scatter in the data, which is due to bead size differences and the resolution in selecting the correct time shift (which is directly related to the sampling frequency), is expected. Further improvements to the velocity measurements can be made by using a faster computer with a larger capacity, thereby almost completely eliminating the error due to the time shift selection tolerance. Overall considerations point to the fact that the technique discussed in this paper provides a reasonably reliable measurement of velocity and temperature profiles simultaneously at multiple locations which cannot be achieved as well or as easily with any other known techniques.

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Table 1 - Thermocouple Calibration Results
Individual thermocouple pair velocity measurement
vs. pitot tube velocity measurement at the calibrator centerline

Pair No.	Flow #1, 62.7 l/min		Flow #2, 47.9 l/min	
	Pitot Tube (m/s)	Thermocouples (m/s)	Pitot Tube (m/s)	Thermocouples (m/s)
1	0.873	0.888	0.669	0.653
2	0.888	0.875	0.698	0.666
3	0.898	0.921	0.693	0.730
4	0.892	0.910	0.725	0.716
5	0.875	0.921	0.721	0.725
6	0.933	0.924	0.717	0.747
7	0.931	0.933	0.755	0.743
8	0.919	0.861	0.745	0.679

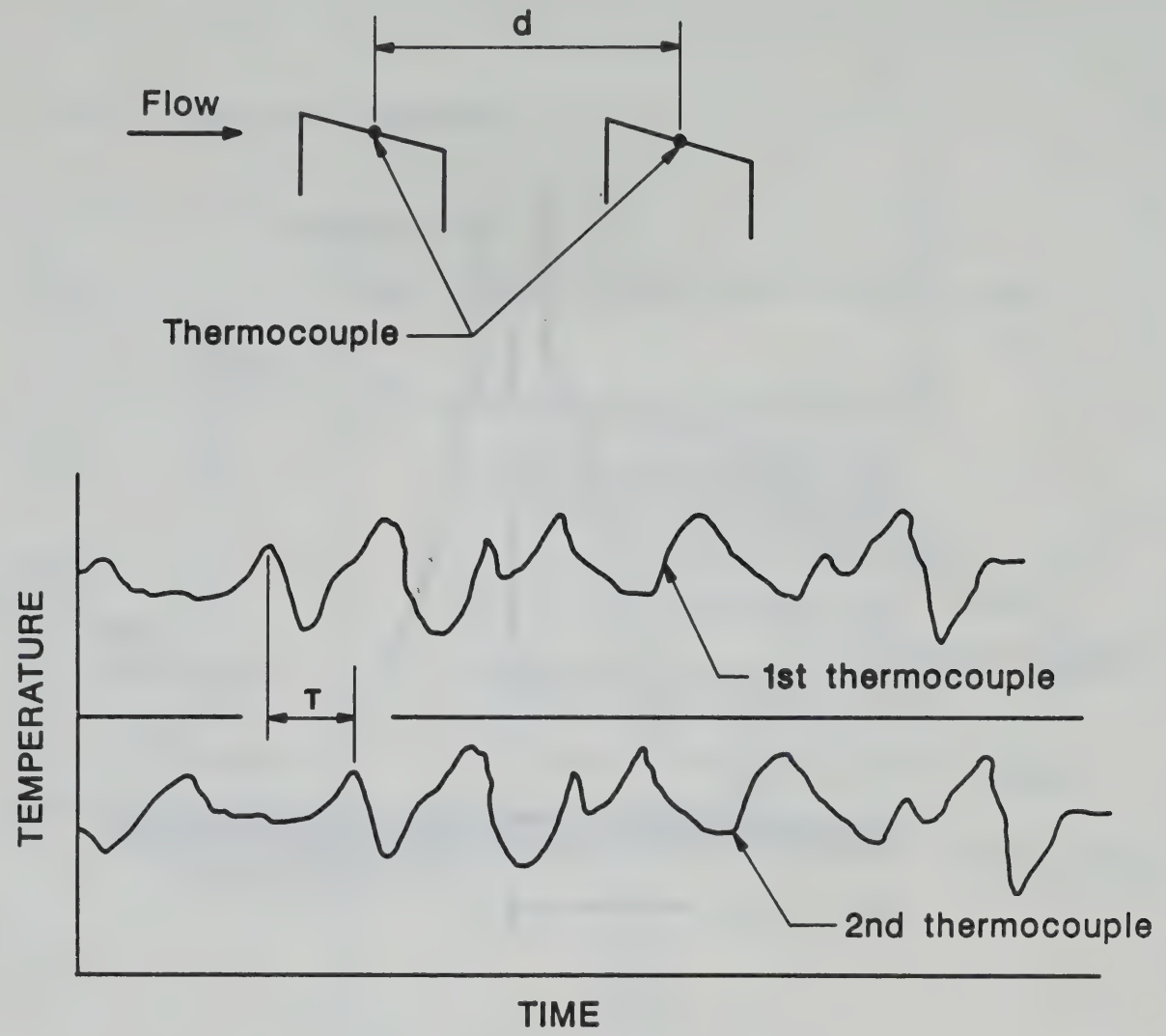

Fig. 1 Illustration of Time Shift in Temperature-Time Records

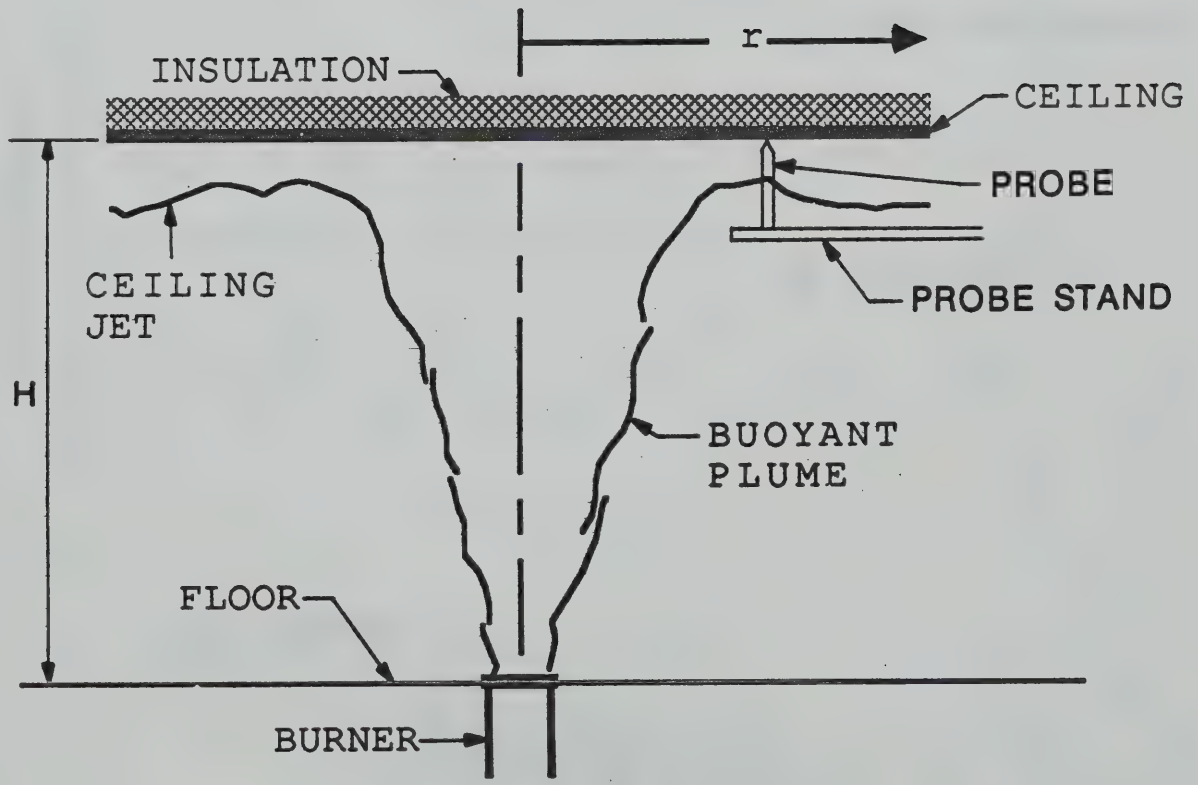

Fig. 2 Experiment Apparatus

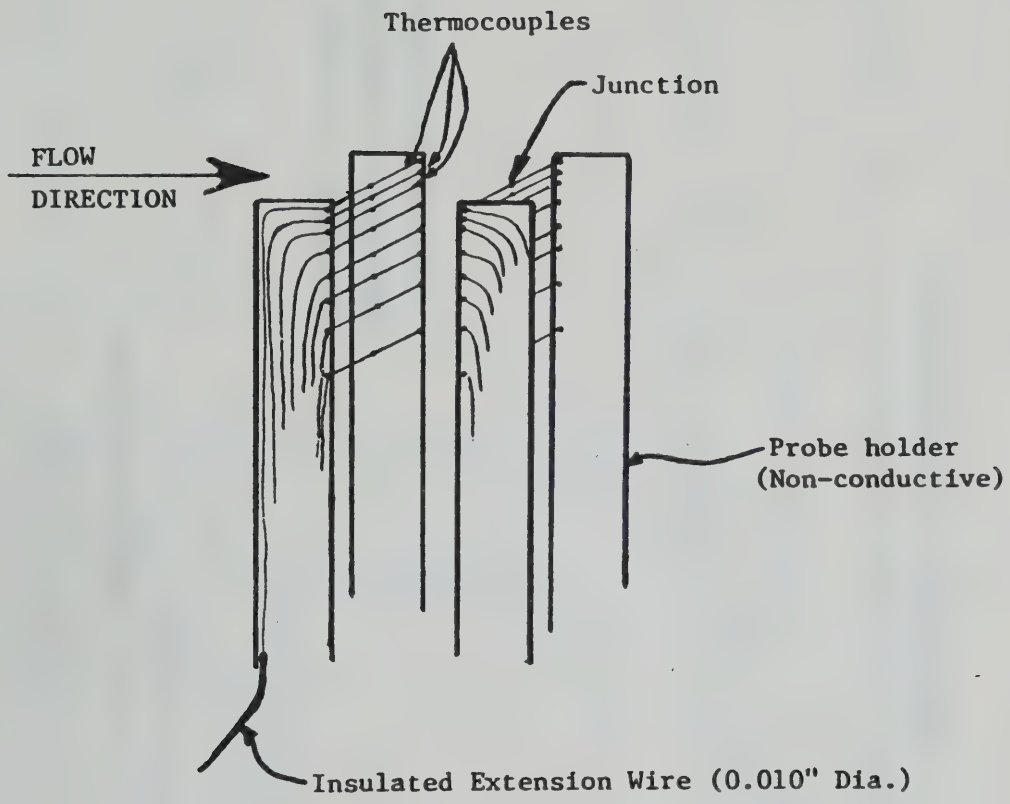

Fig. 3 Thermocouple Probe for Velocity and Temperature Measurements

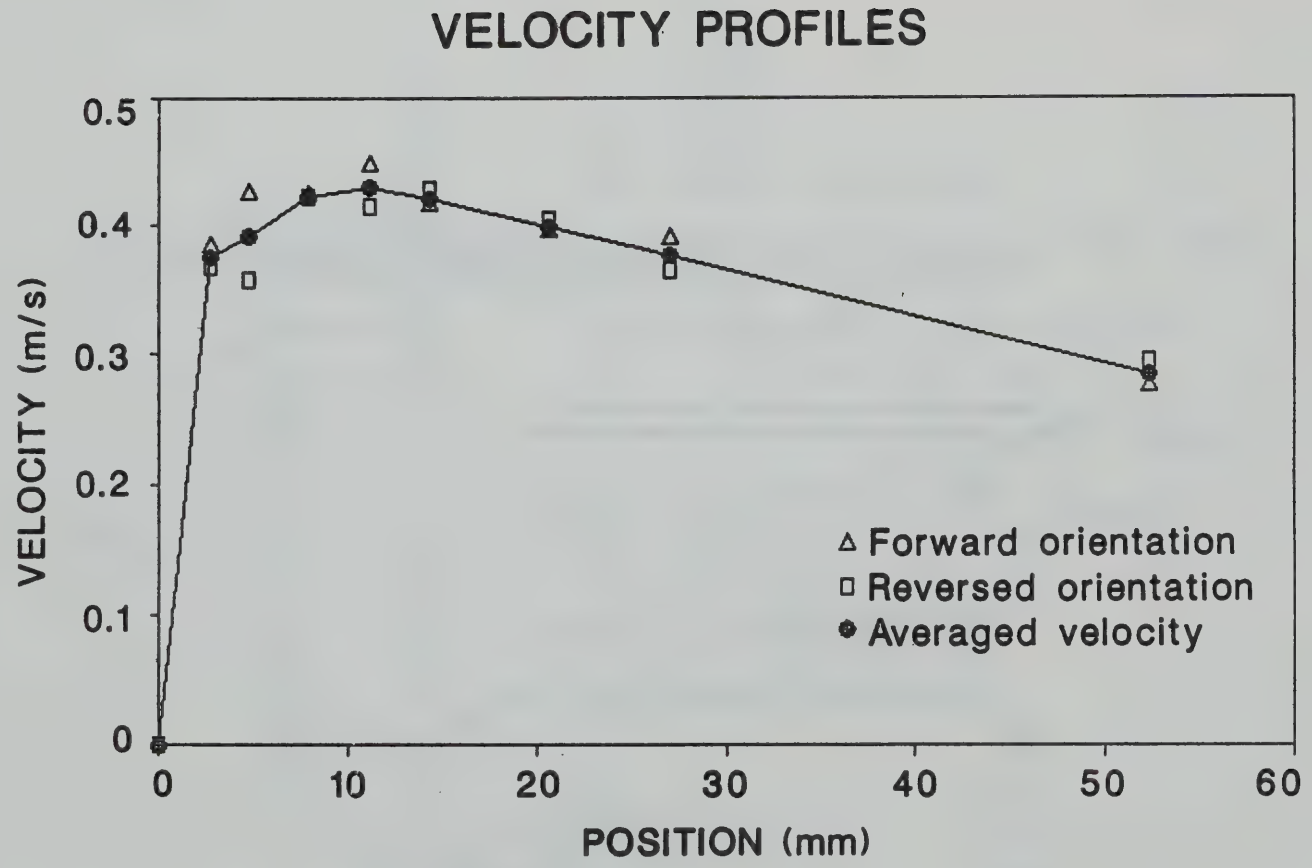

Fig. 4 Steady State Velocity Profiles.
Effect of Thermocouple Orientation.
Q=1.0 KW, H=1.0 m, r/H=0.5

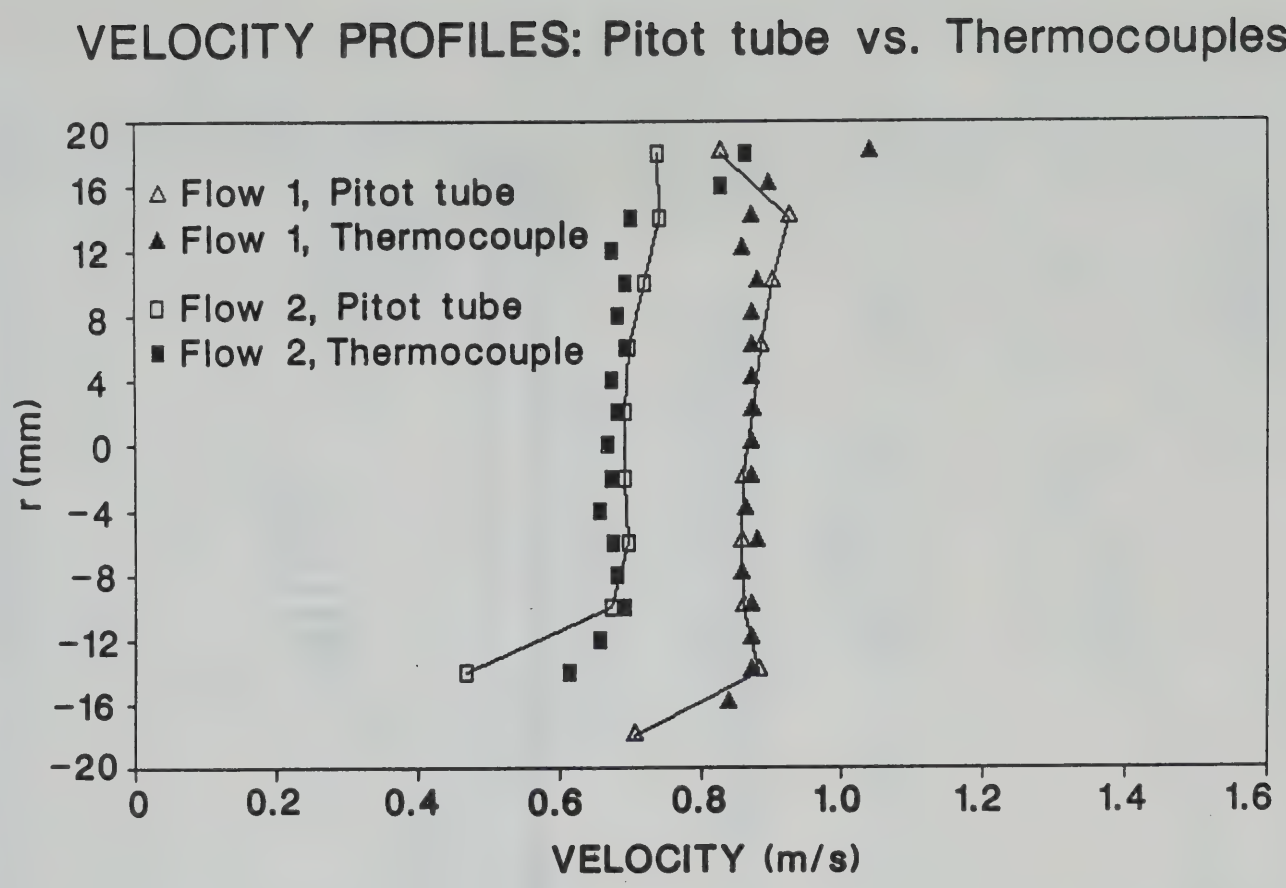

Fig. 5 Thermocouple Probe Calibration Results in Pipe Flow

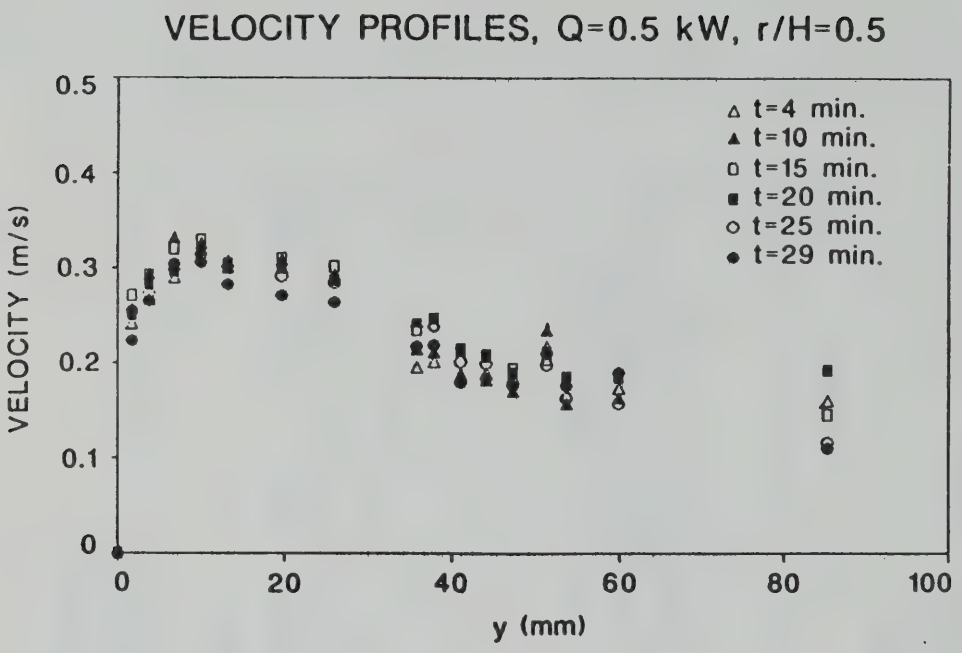

Fig. 6a Velocity Profiles at Various Times
Q=0.5 KW, H=1.0 m, r/H=0.5

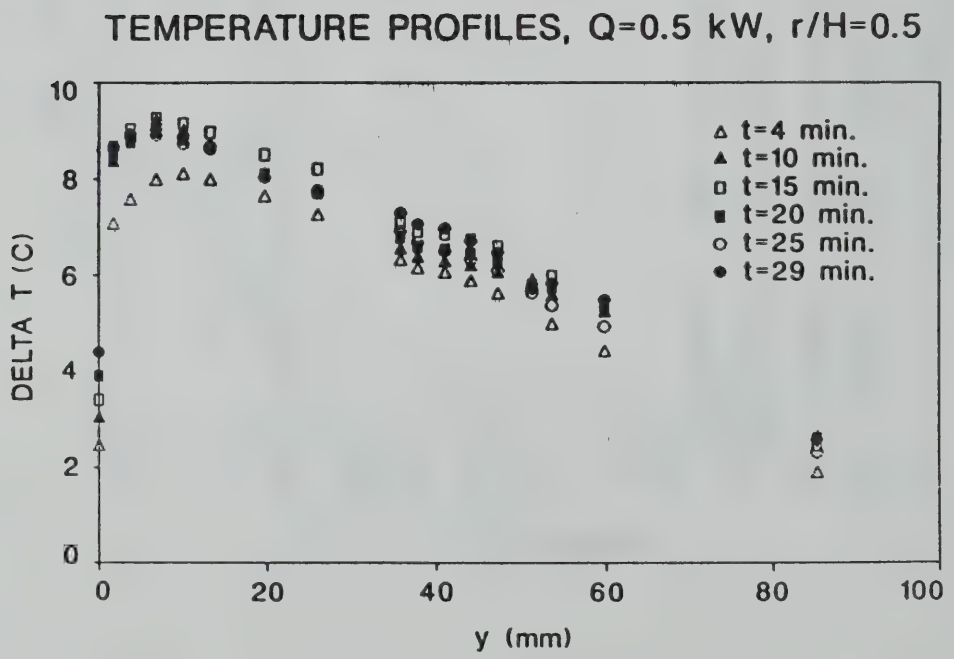

Fig. 6b Temperature Difference Profiles at Various Times.
Q=0.5 KW, H=1.0 m, r/H=0.5

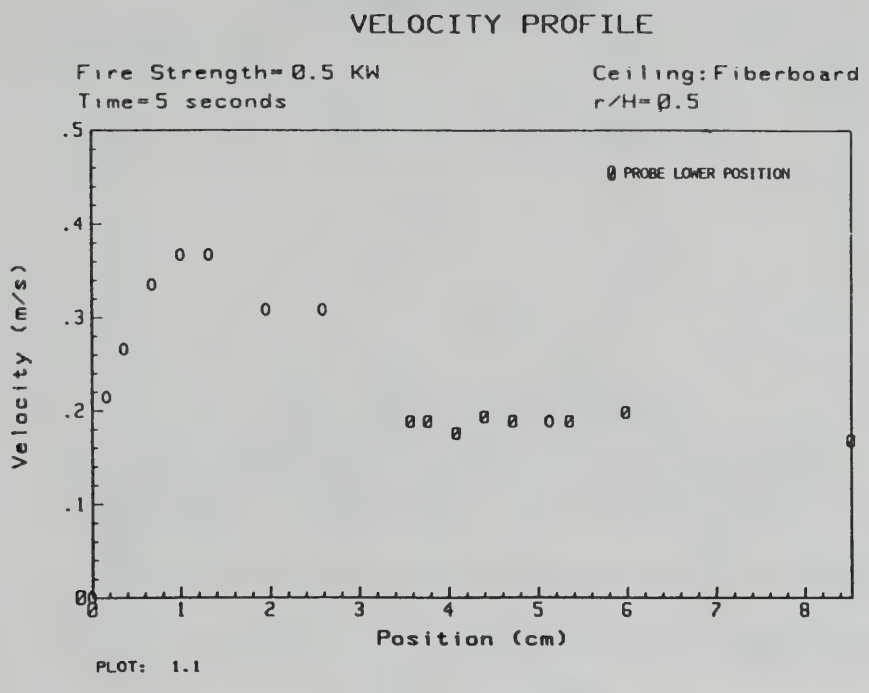

Fig. 7a Velocity Profiles
Q=0.5 KW, H=1.0 m, r/H=0.5

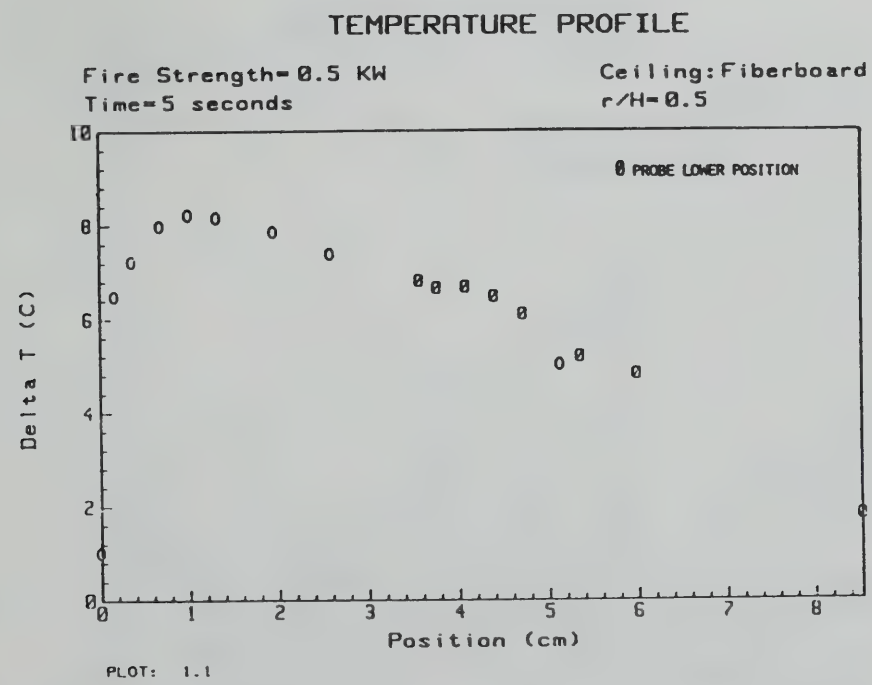

Fig. 7b Temperature Difference Profiles,
Q=0.5 KW, H=1.0 m, r/H=0.5

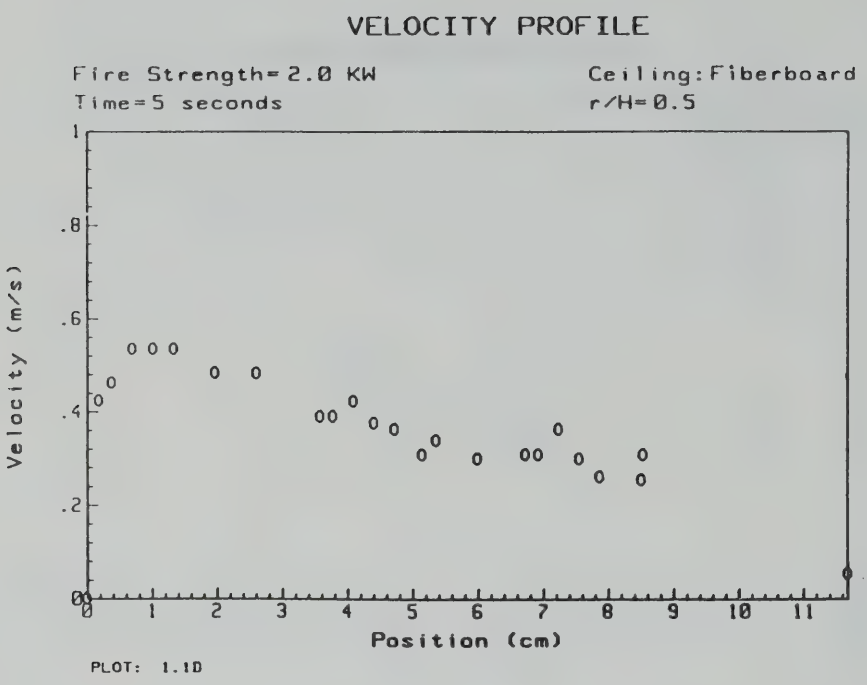

Fig. 8a Velocity Profiles,
Q=2.0 KW, H=1.0 m, r/H=0.5

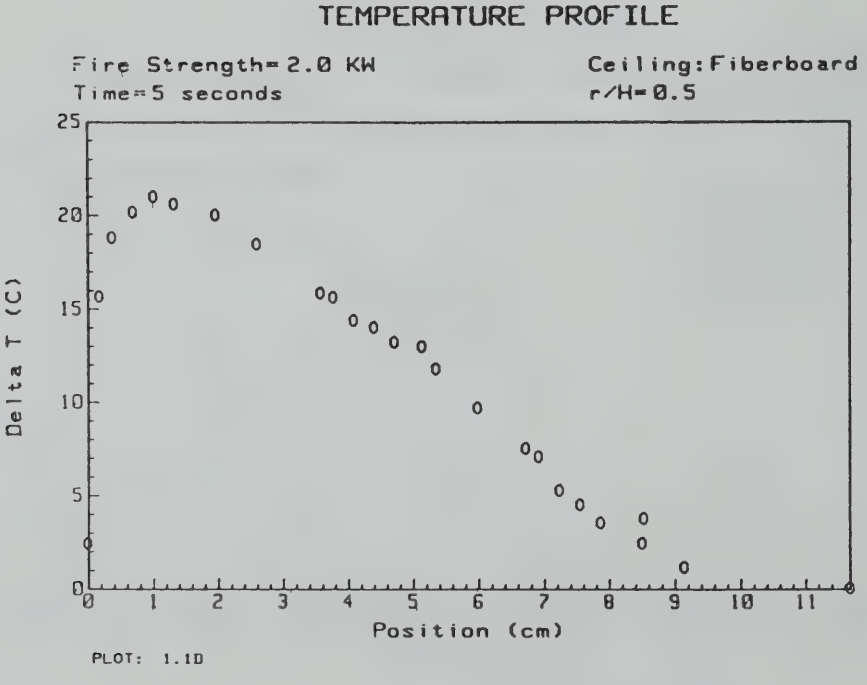

Fig. 8b Temperature Difference Profiles,
Q=2.0 KW, H=1.0 m, r/H=0.5

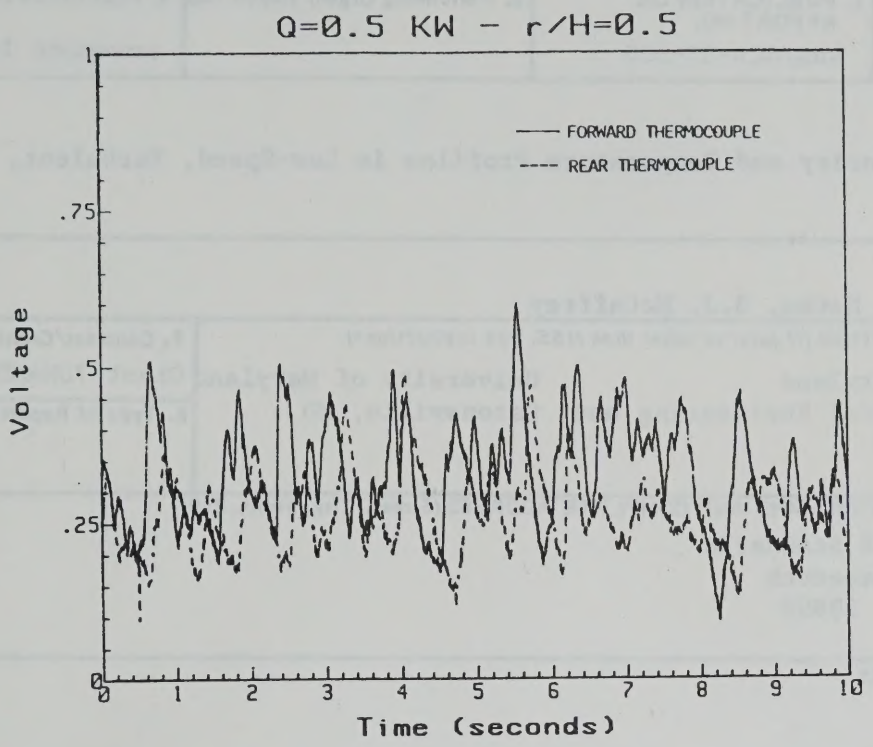

Fig. 9a Temperature-Time Records,
2 mm below the Ceiling, H=1.0 m

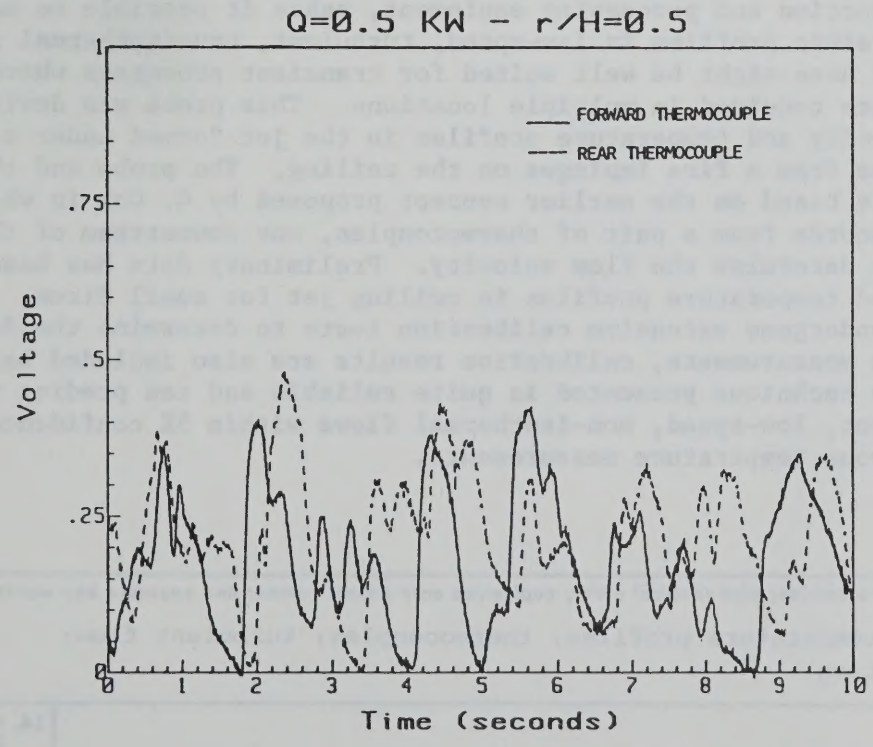

Fig. 9b Temperature-Time Records,
60 mm below the Ceiling, H=1.0 m

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

A probe has been developed utilizing thermocouples as the sensors which, together with associated data-reduction and processing equipment, makes it possible to measure velocity and temperature profiles in low-speed, turbulent, non-isothermal flows, The technique presented here might be well suited for transient processes where simultaneous measurements are required in multiple locations. This probe was devised in order to measure the velocity and temperature profiles in the jet formed under a ceiling when a buoyant plume from a fire impinges on the ceiling. The probe and the technique used in this work is based on the earlier concept proposed by G. Cox in which the temperature-time records from a pair of thermocouples, one downstream of the other, are cross correlated to determine the flow velocity. Preliminary data has been collected for the velocity and temperature profiles in ceiling jet for small fires. The velocity measurements have undergone extensive calibration tests to determine the degree of confidence in these measurements, calibration results are also included here. This work shows that the technique presented is quite reliable and can predict the mean velocity of turbulent, low-speed, non-isothermal flows within 5% confidence while producing simultaneous temperature measurements.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

ceilings; probes; temperature profiles; thermocouples; turbulent flow; velocity distribultion

13. AVAILABILITY

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